CONTROL INTERFACE FOR DRIVING INTERACTIVE CHARACTERS IN IMMERSIVE VIRTUAL ENVIRONMENTS

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ABSTRACT

The effectiveness of training Soldiers in immersive 3D virtual environments is currently limited by character control interfaces that require users to learn actions, for example moving a joystick or pressing a button, that do not necessarily enhance the user's physical performance in equivalent real world tasks and situations. In order to address this need, an advanced man/machine user interface has been developed utilizing inertial position, orientation, ultrasonic range and foot force sensors that allows users to naturally control interactive character movements using sensorimotor responses that closely resemble the tasks and actions performed in the real world. Known as a Virtual Locomotion Controller (VLC), this paper describes the VLC system architecture, control logic and associated sensor processing and the simulation environment used to determine the feasibility of the approach.

1. INTRODUCTION

1.1 Training in Virtual Environments

Advances in the fields of real-time computer graphics, behavioral animation and artificial intelligence are enhancing our ability to create realistic Virtual Environments (VEs) in which participants can acquire skills that are normally too costly, dangerous or otherwise impossible to achieve using traditional training methods. Such virtual training environments will become even more important in the future as program budgets and time for training continue to decrease (Schmorrow et. al., 2001a). Nowhere is this more evident than in the area of military training (Cohn et. al., 2000). Initial strategies and tactics are continually revised and refined, yet Soldiers deployed in the field often have no convenient way to practice or rehearse for new situations, see both the intended and unintended consequences of their actions and acquire new skills and task knowledge through participation in computer simulated scenarios and exercises.

1.2 Embedded Training Systems

The ability for Soldiers to train and rehearse missions with the operational systems deployed in the field is one of the keys to enabling Soldiers to train the way they fight. Some types of virtual training, such as mission rehearsal for vehicles (Cohn, 2001b) can be used to train Soldiers in the field given existing embedded training and simulation capabilities. Others, like training of dismounted infantry, special forces or medical personnel in MOUT environments, which involve complex tasks and significant amounts of interaction with friendly and opposing, are limited by the capabilities of standard computer input devices such as joysticks, keyboards and mice. For example, current embedded dismounted infantry prototype designs consist of wearable user interfaces that allow individual combatants to be immersed in a computer simulated environment with their weapon (Marshall, 2004; General Dynamics, 2004; Quantum 3D 2004). Visual representations of the simulated environment are provided by virtual reality-type, head-mounted display system goggles. Joystick-like controls mounted on a weapon such as the M-4 Carbine are used to control the movement of the user's representation (i.e. avatar) in the virtual world. This type of navigation/locomotion control interface can encumber the maneuverability of Soldiers during critical combat tasks such as looking around corners, moving through buildings and stacking on walls. Because a Soldier's decision-making focus is taken off of the scenario to artificially engage a simulation button, there are tasks introduced that are not present in actual combat (Marshall, 2005). In addition, the development of these systems has demanding man-wearable requirements involving minimal weight and power consumption, fidelity, robustness, accuracy and cost.

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1.3 Need for More Natural and Effective Forms of Avatar Control

One of the keys to enabling Soldiers to train the way they fight is to provide a man/machine interface to embedded training systems that allows users to naturally control the movement of their avatar using sensorimotor responses that closely resemble the tasks and actions they would physically perform in an equivalent real world situation. For example, if a Soldier is performing a task in the virtual world that requires crouching, then he should be crouching in the real world. If he needs to stand up and look around the corner in the virtual world, he should be performing those same actions in the real world. If he is running down a hallway, he should be using his feet to command the desired speed and direction of movement. Such a man/machine interface would not only increase the immersiveness and fidelity of virtual training simulations but would also help maximize training effectiveness by reducing the time required to achieve the same level of proficiency in a live situation.

2. VIRTUAL LOCOMOTION CONTROLLER

2.1 Overview

Virtual Locomotion Control (Marshall, 2005) is defined as "the movement of an entire human body from one location to another, not in reality, but in a virtual simulation environment. It includes the control of all normal human body movements such as standing, kneeling, crawling, crouching, running and walking." This paper outlines an approach to Virtual Locomotion Control (VLC) based on combining data from solid state gyros and accelerometers, ultrasonic range sensors and force sensitive foot pads with real-time inverse kinematic techniques to provide these capabilities. The concept of using real-time inverse kinematics combined with foot force sensing to produce locomotion speed, direction and style of movement command is a relatively new area of research. Related work at the Office of Naval Research (ONR), known as Gaiter (Templeman, 1999) investigated using motion tracking of walking in place to move through a virtual environment. Although this system is capable of distinguishing in-place steps from

actual steps and steps to turn, the type of the motion tracking technology employed and the physical characteristics of the user interface design does not lend itself to embedded training applications..

Developed as part of an SBIR effort with RDECOM (Lane, 2006), the Virtual Locomotion Controller (VLC) system presented in this paper can:

- track the movement and orientation of the user's hands, feet, waist and head using low cost position, orientation and acceleration sensors.

- sense the distribution and magnitude of pressure on the soles of the feet using sensors located in the insoles or attached to the bottom of the user's shoes

- determine the user's current body posture using real-time inverse kinematics based on knowledge of the position and orientation of the hands, feet, head and waist

- produce appropriate speed, direction and style of movement commands by combining information on the user's current body posture with knowledge of the distribution and magnitude of pressure on the soles of their feet

2.2 Virtual Locomotion Controller Design

The Virtual Locomotion Controller system design is shown below in Fig. 1. The main idea behind the VLC is to enable users to specify a character's locomotion style by assuming a body posture normally associated with that type of movement (e.g. walking, running, crouching, etc.), while at the same time controlling locomotion speed through application of foot forces and locomotion direction through body orientation Currently, waist orientation is used to produce direction (i.e. heading angle) commands and forces applied to the toe, heel and/or side regions of the foot are interpreted as positive and negative translational acceleration commands. Simulation results of locomotion in a McKenna MOUT site 3D virtual environment were used to evaluate the effectiveness of the VLC approach.
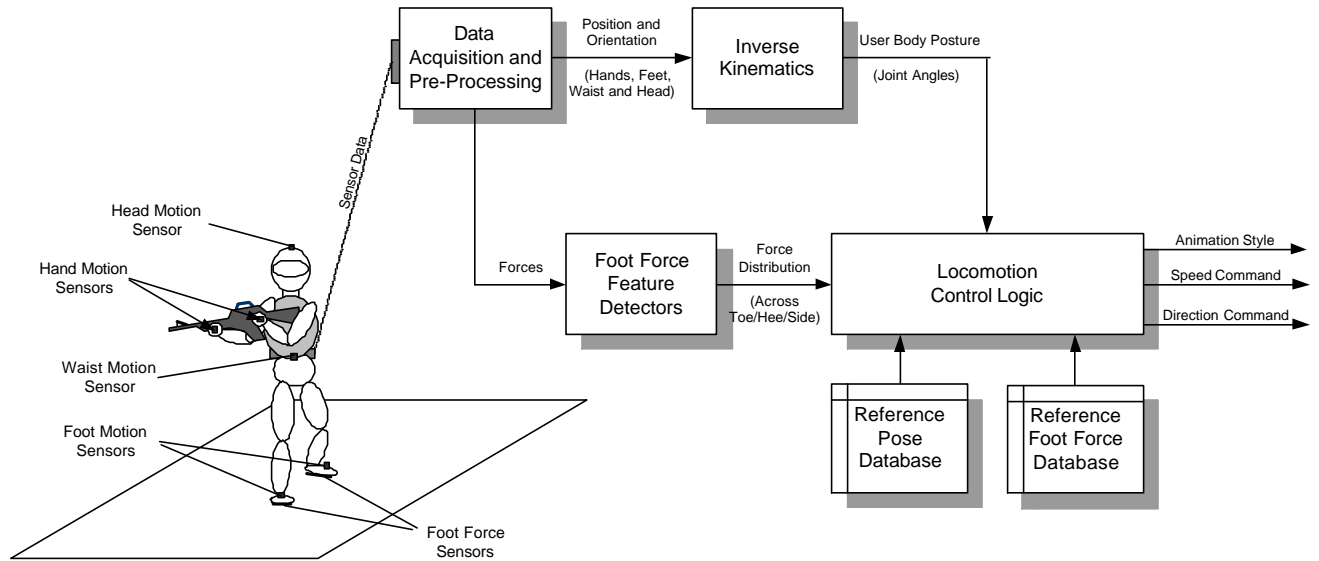
Figure 1. Virtual Locomotion Controller System Design

Real-Time motion Tracking of Body Motions

Real-time tracking of body motions in the VLC is accomplished using inertial measurement unit (IMU) motion tracking technology based on solid state gyros and accelerometers (Analog Devices, 2006; Microstrain, 2006; and Intersense, 2006) and ultrasonic range sensors (Hexamite, 2006). These sensors, shown below Figs. 2a and 2b below, are attached to the hands, feet, waist and head as shown in Fig. 3.
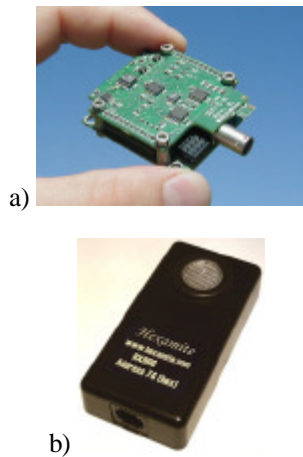

Figure 2. a) Inertial sensor devices manufactured by Microstrain, Inc. and b) Ultrasonic sensor device manufactured by Hexamite, Inc.

The IMU sensors provide orientation data in the form of rotation matrices, Euler angles and quaternions, as well as acceleration data in body-relative coordinates. The ultrasonic sensors provide data representing the distance (or range) between the hands, feet, head and waist, shown as the blue and green lines in Fig. 3.
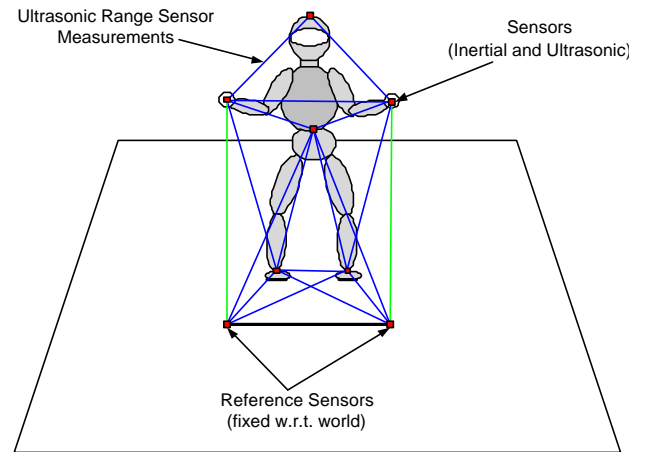

Figure 3. Range sensor measurements

Real-Time Tracking of Foot Forces

Foot force sensors, such as those manufactured by (Tekscan, 2006), shown below in Fig. 4, allow real-time tracking of foot pressure and force using paper-thin reusable sensors placed in the user's shoes. The sensors produce data such as that shown in Fig. 4b that is used by the Virtual Locomotion Controller to compute speed commands, as explained in Section 2.3.
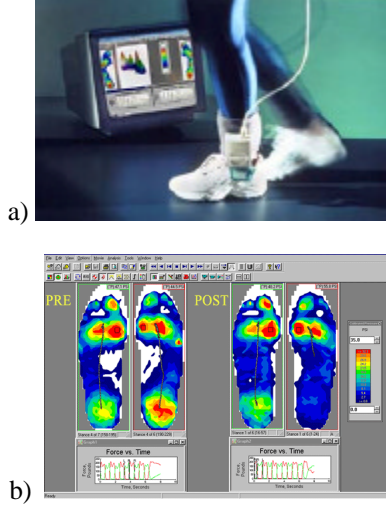
Figure 4. Fscan foot force tracking system. a) physical devices attached to feet. b) pressure distribution and force output patterns produced by each device.

Sensor Data Processing and Feature Detection

Ideally, the position of the inertial sensors would be obtained by double integrating the IMU accelerometer outputs. Unfortunately, due to acceleration bias errors of approximately 10 mg, (g = 32.2ft/sec^2 or 386.4 in/sec^2) this quickly leads to divergence in the position measurements. For example, over a 1 sec interval the position error would be approximately 3.864 inches, over a 2 sec interval 15.45 inches, which is unacceptable for the VLC application. This is what motivated the need to incorporate ultrasonic range sensors to bound the error. Using a total of 8 ultrasonic sensors, two located on the floor (to provide a world reference) and one attached to the left foot, right foot, left hand, right hand, waist and head, algorithms were developed (based on the triangulation approach described in (Lane, 2006) to allow the position of the feet and waist (that is, their x, y and z coordinates) in world coordinates to be computed from the range data obtained from each of the ultrasonic sensors. The ability to use only two references sensors fixed in the world (horizontally) as shown in Fig 3, along with knowledge of which foot is in contact with ground to obtain estimates of (x,y,z) device positions was one of the unique aspects of the triangulation approach developed.

The sample rate for the position estimates obtained from the ultrasonic range sensors is on the order of 1 Hz. A more frequent (i.e. higher sample rate) and accurate estimate of the position of the feet, waist and hands, however, can be obtained by combining the ultrasonic position measurements with the IMU acceleration measurements using a Kalman filter, as shown below in Fig. 5. The techniques described in (Bar-Shalom et. al, 2001; Foxlin, 1996) were used as the basis for such an approach.
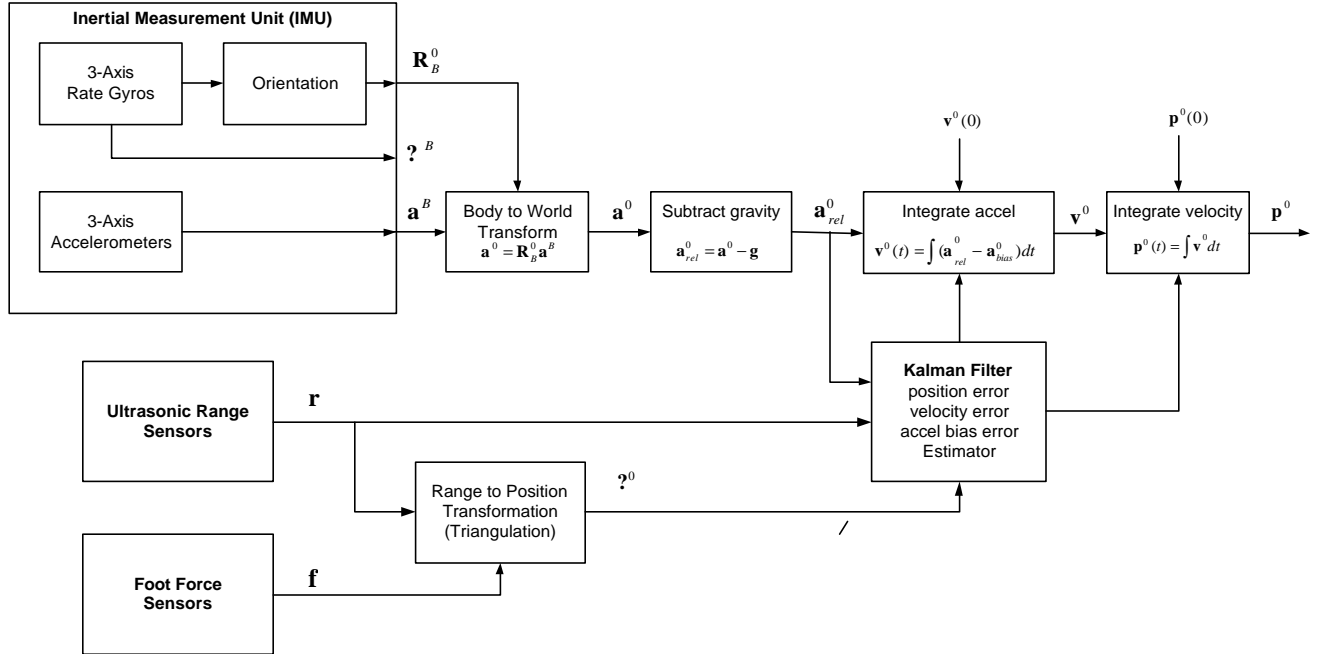

Figure 5. Estimating body position by combining ultrasonic position measurements with inertial acceleration measurements using a Kalman Filter approach (Bar-Shalom et. al, 2001; Foxlin, 1996).

Foot force feature detectors also were developed that allowed the center of force and the magnitude of force applied to each foot to be determined. This was accomplished by weighting the (x,y) location of each Fscan grid element by the magnitude of the associated force, summing the weighted x and y components and dividing by the total force across all grid elements. Additional feature detectors also were developed to determine the location of the foot forces in terms of heel or toe regions as well as whether the forces were being applied to the left or right sides of the foot. These heel, toe and side regions of the feet are shown below in Fig. 6

Figure 6. Heel, toe and side contact force regions

Inverse Kinematics

Knowledge of the position and orientation of the hands, feet, waist and head allows the real-time inverse kinematics algorithms (Handelman et. al., 2000) to determine the user's body posture (in terms of joint angles at the ankle, knee, hip, etc.) from knowledge of the position and orientation of their hands, feet, waist and head. User body posture is then used by the VLC shown in Fig. 1 in two ways: 1) to determine the style of movement during locomotion tasks (for example, walking, running, crouching, etc.) and to track the user's body movement during non-locomotion tasks to correlate the movements of their avatar in the virtual world to the movements and actions they are performing in the real world (for example, looking around corners, ducking, hand signals such as pointing, waving, etc.)

2.3 Virtual Locomotion Control

Virtual Locomotion Control allows users to control not only the speed and direction of their avatar's movement, but also the style of the associated animation. The ability to determine position, orientation and force distribution across feet allows the system to distinguish between locomotion and standing modes of operation.

Longitudinal Speed Control

User's are assumed to be standing and control the longitudinal speed of motion primarily through forces applied to the toe and heel regions of the feet. The simplest way to produce forward speed commands is to apply foot contact forces in the green areas of the right foot, as shown in Fig. 7.

Figure 7. Regions for producing forward (green) and braking (red) movement commands

Using this approach, the harder the user presses down in the green area the faster the avatar will go. The actual speed command generated is dependent upon the magnitude of the force and the size of the contact area in which the force is applied. In addition, the red area of the right foot represents the region where the user can generate contact forces that are interpreted as braking (or backward movement) commands. That is, commands that can be used to reduce the forward speed. The approach outlined above only depends upon the magnitude of the contact forces generated in each region and is independent of the orientation of the left or right foot. An additional mode for controlling forward and backward movements was also investigated that produced speed commands proportional to the distance of the center of force from the boundary of the heel or toe region. Since this mode is independent of the magnitude of the applied foot forces, it is not affected by user size or weight. However, it is not as intuitive, since applying more force in the same location (i.e. pressing down harder with the foot) has no effect on the speed of the avatar's movements.

Lateral Speed Control

In cases where the user wants to produce a command for a side step style of locomotion, the orientation of the feet can be taken into account as well as the magnitude of the forces generated in the blue regions of each foot. This is shown below in Fig. 8. The blue areas represent regions where the user can generate contact forces that initiate a side step command for each foot where the size of the step can be proportional to the magnitude of the force generated .

Figure 8. Regions for producing side step (blue) movement commands

Shown below in Fig. 9 are the foot positions corresponding to a left side step and right side step command from a standing (i.e. stop) pose. Anytime the user assumes the stop pose (i.e. feet in L0, R0 position), the character locomotion will smoothly come to a stop. Starting from the stop pose, the foot position sequence (L0, R0) -> (L1, R0) -> (L0, R0) will cause the character to take one side step to the left while the sequence (L0, R0) -> (L0, R1) -> (L0, R0) will cause the character to take a step to the right. Additional foot position sequences can be defined in a similar way allowing the user to command the character to take one step forward, one step back or one step diagonally up to the right, diagonally up to the left, diagonally back to the right or diagonally back to the left.
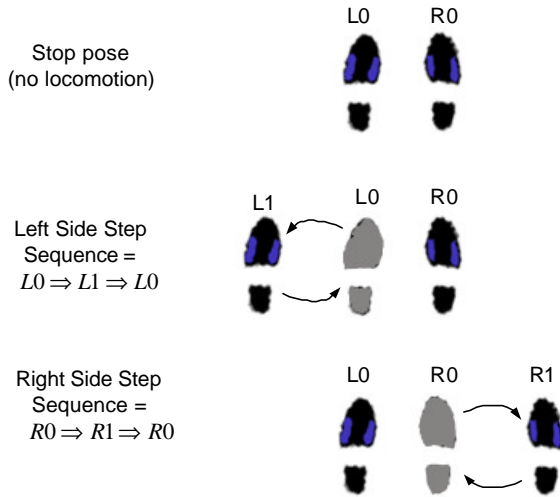

L0   R0

Stop pose
(no locomotion)

L1   L0   R0

Left Side Step
Sequence =
$L0 \Rightarrow L1 \Rightarrow L0$

L0   R0   R1

Right Side Step
Sequence =
$R0 \Rightarrow R1 \Rightarrow R0$

Figure 9. Side Step command sequence

Directional Control

In the present VLC system, the relative orientation (i.e. yaw angle) of the user's waist with respect to their feet is used to determine a directional rate command. This type of directional control scheme, known as "waist steering", enables head movements to be decoupled from body movements, thus allowing the user to freely look around while they move in the direction in which their body is currently pointing.

The orientation of the feet, as shown below in Fig. 10, is used to determine the yaw angles corresponding to zero, min and max steering rate commands. The zero steering rate command is associated with the angle which is the midpoint of the angle between the two feet. The directional rate command ($\dot{y}$) is then integrated to specify the direction of travel (i.e. heading angle) in which the avatar should move in the virtual environment.
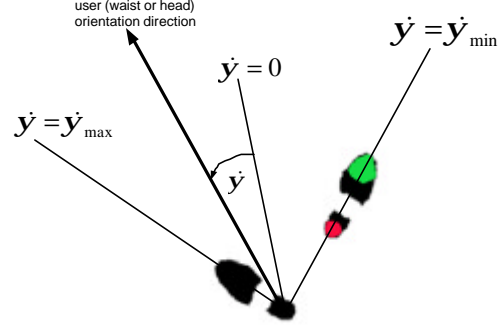

Figure 10. Calculation of Steering Rate commands

Style of Locomotion

As shown in the VLC design of Fig. 1, the locomotion control logic uses information about the current body posture and the force distribution across the toe, heel and sides of the feet to determine the style of the resulting locomotion. The reference pose database contains a set of body poses characteristic of the various styles of locomotion that can be used to animate the avatar. For example, poses that represent crouched walking, walking while aiming a gun, side stepping, etc.). If it is determined that the user's current body pose matches one of these reference poses in the database (by determining the distance between the joints in the current pose and the reference pose) and the foot forces are consistent with these poses (as determined by the foot force database), then the locomotion style command is automatically updated. This allows the user to perform actions comparable to what they would do in the real world (for example, walk, crouch, sidestep, etc.) and have the system automatically generate animations that reflect this. In addition, the system can automatically generate animation style commands changes representing transitions between walking, jogging and running animation based on the speed of the commanded movement.

2.4 Test and Evaluation

In order to test and evaluate the effectiveness of the Virtual Locomotion Controller a 3D simulation testbed environment was developed. A screen shot from the simulation is shown in Fig. 11. This simulation utilized a third person camera that allowed the user to see the effect of their body movements on the resulting character motions. First person perspectives could also be accommodated in the simulation by locating the camera at the character's head. The intent of this simulation testbed was to evaluate the ease in which a user could learn to control a character using the VLC interface. User's controlled the Soldier character by using the waist steering mode to specify locomotion direction (i.e.

heading angle) and foot forces applied to the heel and toe of the right foot to regulate speed of movement. A simple grid-based world was first used to allow the user to quickly master the VLC user interface. This was accomplished by having the user control the character to follow a series of grid lines on the floor in order to calibrate the effect of their body movements on the resulting character's speed and direction of movement. Preliminary test results confirmed that users were able to easily control the character to follow the grid lines with only a few minutes of practice.

A more complex terrain model (based on the McKenna MOUT site) was also used to evaluate the

VLC performance, where user's could command the character to side step and crouch in addition to controlling character speed and direction. IK allowed tracking of the user's feet when in a standing (i.e. feet parallel) locomotion mode. Additional locomotion control modes also were implemented to allow users to maintain the character's upper body orientation towards a target while independently controlling the locomotion direction. Preliminary results from the simulation testbed indicate that the VLC system design provides users with the ability to independently control speed, direction and style of the resulting character motion.

Figure 11. VLC Simulation Testbed Environment

CONCLUSIONS

There are many advantages to the Virtual Locomotion Controller described in the paper:

- Provides users with a more natural and intuitive interface for controlling the movement and body posture of characters in first person 3D training applications,

- Utilizes sensorimotor responses that closely resemble the tasks and actions users would physically perform in equivalent real world situations,

- Leaves hands free to perform other tasks (e.g. signaling gestures, aim weapon, etc.),

- Increases user's sense of immersion in virtual reality training simulations while at the same time providing higher fidelity control over character movements and actions

The VLC provides a novel user interface/game controller potentially usable with a wide range of software (training, simulation, education, entertainment) and hardware platforms (PCs, embedded systems, handhelds and game consoles). Possible applications

include: embedded dismounted infantry training systems, virtual reality and commercial 3D computer games, sports training and first responder/homeland security simulation systems.

Future work includes improving VLC system robustness to sensor occlusion, noise and environmental disturbances, investigation of usability issues in typical dismounted infantry tasks, such as room clearing, and development of an ruggedized, fully wearable second generation prototype.

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